IO'S THERMAL **ANOMALIES &** HEAT FLOW; D. L. Matson, Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109

Our vision of Io's geology and geophysics is continuing its relatively rapid evolution which was kicked-off by the discovery of active volcanism by Voyager. The thermal anomalies on Io provide a continuing way to observe and study 10's volcanism using ground-based astronomical telescopes and infrared, spectral radiometry. Such observations can see actual eruptions and provide the data for a quantitative assessment of eruption parameters and identification of the style(s) of volcanism. A more fundamental characteristic of Io, however, is the large amount of heat that is being radiated by the anomalies. In all, it is *some* 1.06x 10^{14} W! Averaged over 10, this would be 2.55 W/m*. On the Earth this is a level found only in the localities of the more active geothermal areas. The only mechanism which can provide this much power is tidal dissipation, Because of this fact, Io's heat flow can be coupled through the equations for tidal dissipation to properties of Jupiter's interior and to the tidal evolution of Io's orbital parameters. This large heat flow is also a key constraint on models for Io's interior. Because of these relationships, heat flow is not only important for understanding Io, but in addition has fundamental implications for the state and evolution of the jovian system!

The subject of Io's thermal anomalies and volcanism is covered by several excellent, published reviews (1 ,2,3). They also serve as chronicles of the observational history. The intent of the present review/tutorial is to focus on current developments toward obtaining an accurate value for Io's *mean heat flow*. In particular, I will discuss three ongoing, independent and convergent approaches toward measuring Io's heat flow. These are- 1) interpretation of ground-based integral radiometry as a function of longitude, 2) further analysis and refined interpretation of the Voyager IRIS data, and 3) analysis of transient outbursts believed to be due to volcanic eruptions and constraints on Io's rate of resurfacing.

While Voyager discovered volcanism and thermal anomalies on 10, it was an analysis of ground-based telescope data that yielded the first indication of the surprising high value of the global heat flow (4).' This approach uses whole disk, multi spectral radiometry of Io. At the present, this data set spans about a decade, with some key observations dating back to the early '70's. It shows the continuing anomalies as well as some spectacularly large outbursts due to lava eruptions. The thermal anomalies show up as enhancements over and above the *background spectrum* which is due to heat that is produced by the absorption of sunlight. For Io the absorption of sunlight and the subsequent reappearance of that power as emission in the infrared spectrum are not well described by the usual modelling techniques for airless bodies. Furthermore, as additional constraints such as albedo and spectral emissivity emerged from the continuing analysis of Voyager data, even those models which were thought to be reasonably accurate were invalidated. Also, in the past it had been general] y assumed: 1) that the thermal anomalies or "hot spots" were much warmer than the ambient surface of Io, 2) that there was no significant background flux at 4.8 μm, and 3) the flux at 20 μm did not have a significant flux due to the anomalies. In the light of the new work, none of these are even reasonable approximations.

Recently, there has been progress on this front with the recognition of an effect which is prominent in the radiometry data and with the introduction of a revolutionary thermophysical model for Io's surface (5). The *thermal pedestal effect is* a spectral blue-shift which occurs in the background spectrum when sunlight is absorbed on a positive thermal anomaly caused by heat flow. Recognition of this effect has led to the concept of *active* and *passive* components of the background spectrum. Passive components can be calculated *a priori,* while the active components cannot be computed until after the night-time temperature of the anomaly is known. Another novel feature of the model is the radiation of much of the background flux during the nighttime. This is accomplished by employing a thermal reservoir unit. The model solves what has been the chief problem in modelling Io's background, namely, the low value of flux density observed at 20μm. The calculation of the background flux is done more accurately. This in turn has allowed the recognition of large, lower temperature thermal anomalies. As a result, the value for heat flow has been increased, going up to 2.55 W/m* for the global average.

Further study of the IRIS data set (6) is another approach to estimating the global heat flow. This data set has been revisited by McEwen *et al.* with better pointing information and it has been possible to recognize larger, lower temperature anomalies than before (7). The current global estimate by this approach is about 3.5 W/m^2, though it must be kept in mind that there are IRIS data for only about half of Io.

The large (in terms of 4. 8pm flux density), high-temperature outbursts are on the third path toward heat flow estimates. This approach, first suggested by Reynolds *et al.* (8) and further developed by Carr (9), combines estimates for the frequency of eruption with a bound on Io's resurfacing rate. High temperature, short lived events have been recognized since before Voyager, During the multi-wavelength radiometry program such events occurred about 5 % of the time (5, 10). Several events have been observed with temperatures near 1,000 K, far too high a temperature to be explained by a sulfur lava. The conclusion has been drawn that these are due to silicate lava, which are more consistent with Io's bulk density than sulfur, and perhaps similar with lavas on the Moon and on the Earth. The lack of impact craters on Io provides a bound on the resurfacing rate. Modelling an outburst as a lava flow, assuming an average flow thickness (about 10 m), spreading rate can be used to obtain discharge. Discharge combined with the exit temperature gives the amount of heat brought to the surface. One example of this approach yields a heat flow of about 2.7 W/m* (10).

In conclusion, our knowledge about Io's thermal anomalies is continuing to advance, and three independent approaches are yielding heat flow estimates of about 3 W/m^2

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